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The evolution of Hadean–Eoarchaean geodynamics

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ABSTRACT

Geodynamic modelling of Hadean/Eoarchaean tectonics typically requires higher rates of internal heat production, and higher mantle temperatures, in models that possess temperature-dependent viscosity and a yield criterion. In such models under Hadean conditions, for a wide range of geodynamic configurations and modelling approaches, subduction has a propensity to fail. This has led to the suggestion that the predominant tectonic regime in the Hadean was stagnant-lid convection, with intermittent recycling events. Various lines of evidence support this suggestion, from i) the long mixing time of mantle isotopic anomalies or compositional heterogeneities, such as ^{142}Nd, ^{182}W, and platinum group elements, to ii) the long residence time of the Hadean protolith to the Jack Hills zircons, and iii) thermal evolution models, which typically require lower heat flux in the past to avoid the "Archaean thermal catastrophe". The framework provided by stagnant lid, or episodic overturn, convection, iv) provides an explanation for the formation of early Archaean TTGs and greenstones, and v) explains the interleaving arc-plume sequence observed in many Archaean terranes, suggesting subduction initiation events may have been common, increasing their preservation potential. Implications include a low magnetic field strength in the Hadean, which is consistent with emerging paleointensity data from these times.

1. Introduction

The Hadean was an eon of extreme violence. It may be considered to have begun immediately post moon-forming impact, when the entire planet was thought to be covered by a magma ocean between ~300 and 2000 km deep (Solomatov and Stevenson, 1993; Solomatov, 2000; Elkins-Tanton, 2008). This impact may have been preceded by others of similar magnitude, leading to multiple magma oceans, suggested by noble gas systematics (Tucker and Mukhopadhyay, 2014). The interaction of the nascent moon with a global magma ocean may have resulted in significant tidal heating, maintaining super-solidus surface temperatures for ~2 Myr (Zahnle et al., 2007). Post Moon-formation, the Hadean experienced ongoing meteoritic bombardment, culminating in the late heavy bombardment in the Eoarchaean (Bottke et al., 2012), which may have both impinged on the preservation of older terranes (Marchi et al., 2014), and perhaps facilitated early tectonics (Hansen, 2007). The freezing of the magma ocean may have formed an unstable cumulate sequence (Elkins-Tanton et al., 2003), the overturn of which could have had a profound influence on the planet (e.g. Debaille et al., 2009). During this time, Earth lost much of its early atmosphere, due to both hydrodynamic outflow and impact erosion (e.g. Pepin and Porcelli, 2006). At some point, a steam atmosphere rained liquid water, forever changing the geochemistry of the surface. The primordial heat, from accretion, impacts, core-formation, and high internal rates (not just from conventional isotopes, but also short-lived isotopes such as ^{26}Al and ^{60}Fe), would have fundamentally affected the thermo-mechanical character of the planet. Somewhere in this chaos, early differentiation events left an indelible mark on the mantle, to be later sourced by younger igneous rocks (Debaille et al., 2013). Zircons were forming in evolved magmas, which would survive, in later sediments like the Jack Hills conglomerate (Valley et al., 2014), till the present day (Wilde et al., 2001). The Earth's oldest rocks may have been formed (e.g. O'Neil et al., 2012). And either during, or shortly after in the Eoarchaean, life somehow evolved (e.g. Buick et al., 1981).

Despite its clear geological interest, the Hadean is severely understudied, primarily due to the lack of geological constraints or a crustal record as by definition. The Eoarchaean crust gives us insight into the state of the planet immediately after the Hadean, and provides somewhat equivocal constraints on Hadean evolution. In additional, recent observational advances are now able to lay some constraints on geodynamic processes operating in the

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Eorchaean and Hadean (e.g. Debaille et al., 2013; O'Neill et al., 2013a) – though often the context and implications are far from clear.

From a geodynamics perspective, the Hadean is critical for another reason. Recent work has shown the importance of initial conditions on the subsequent evolution of planets (Crowley and O'Connell, 2012; Weller and Lenardic, 2012). A planet may evolve down fundamentally different paths, and exhibit completely different tectonic pathways, depending on its starting temperature (O'Neill et al., submitted for publication). And so while the Hadean has hitherto been considered a geological dark age, for modelling as well as geology, it is becoming increasingly important to address the state of the planet during the epoch, in order to comment sensibly on any aspect of Earth's thermal or tectonic evolution.

A number of disparate studies, utilising very different tools and configurations, have been applied to the Hadean recently. An important question is: do these numerical models have common ground? And what can be discerned about the nature of Hadean geodynamics from their behaviour? From the point of Hadean geological observations: what sort of constraints can currently be applied to Hadean geodynamics? The purpose of this contribution is to bring to light the important and often overlooked coherence of conclusions of what has hitherto been the Hadean geodynamics underground, and to cast the main consistent result of these simulations – the shutdown of subduction under Hadean conditions – in the framework of the existing observational constraints.

2. The Hadean geodynamics underground – the effect of internal temperatures on tectonic evolution

Addressing the question of whether or not the Hadean had plate tectonics minimally requires a capacity to simulate tectonic regimes, under the thermal conditions appropriate for the Hadean/Eoarchaean. A fundamental difference between the Hadean mantle and the present day is the effective mantle temperature, and most studies have simulated early Earth conditions by increasing heat generation rates, or changing the mantle temperatures, to those appropriate for the past. This in itself is problematic. A recent compilation of mantle temperature estimates through time (Herzberg et al., 2010), though limited, suggests minor mantle temperature differences throughout the early Archaean – leading to the speculation that despite much higher heat production rates, the Hadean mantle may not have been significantly hotter than the Archaean.

A number of early works addressed simple convecting systems under the hotter conditions appropriate for the early Earth (e.g. Richter, 1985; Jarvis, 1984), and highlighted an association between high heat production/mantle temperatures, with high heat flows, and plate velocities. These generally lacked the prerequisite physics to address the tectonic problem, however.

Davies (1992) used a simple scaling argument relating oceanic crustal thickness, and buoyancy, to a parameterised model for mantle temperature, and suggested that subduction would be unfeasible for times earlier than ∼1.5 Ga, due to positive buoyancy of plates arriving at subduction zones. Following the suggestion from Hadean zircon studies for an extensively depleted Hadean mantle (Harrison et al., 2005), Davies (2006) revisited the problem of oceanic crustal thickness. He used numerical models of convection with differentiation and found that gravitational settling of a mafic component facilitated the development of a depleted upper mantle, which in turn would result in a comparatively "thin" oceanic crust – facilitating plate tectonics. The models of Davies (2006), however, prescribed plate motion, and so while alleviating issues with compositional buoyancy and subduction, do not address the thermomechanical question of whether the prescribed tectonics is actually feasible.

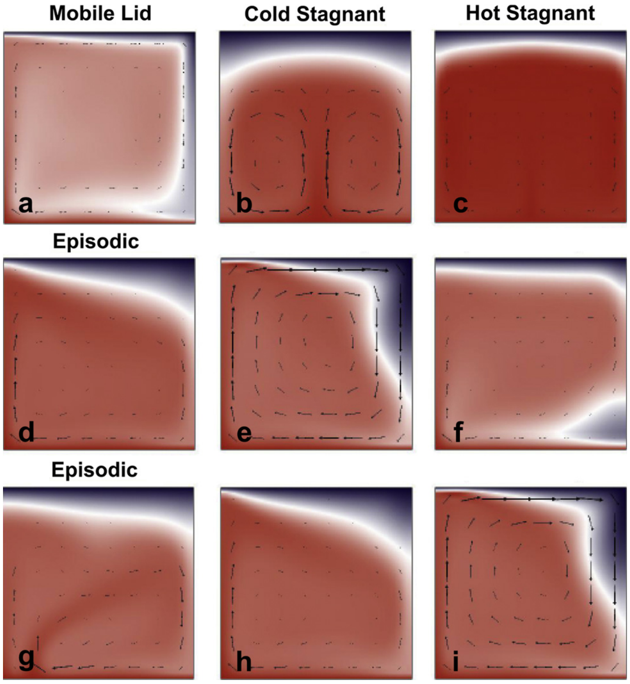

Fig. 1. Convection in mobile, stagnant and episodic regimes, for a nominal Rayleigh number of 1×10^7 (based on a non-dimensional basal temperature of 1), a Frank–Kamenetskii viscosity contrast of 3×10^4 (similar to Moresi and Solomatov, 1998), and a Byerlee yield criterion (Cohesion $B_0 = 1 \times 10^5$, $B_z = 1 \times 10^7$, see Moresi and Solomatov, 1998, for details). a) System displays mobile lid behaviour for $T_{\text{base}} = 1.1$, internal heating $Q = 0.5$. b) The same system exhibits stagnant lid dynamics if the basal temperature is dropped to $T_{\text{base}} = 0.8$, other parameters being the same. c) If the systems internal heating is increased to $Q = 6$, the system enters a "hot stagnant" regime. d–i) Timeshots of an episodic overturn regime simulation, for a system similar to a) with $Q = 0.5$, but here $T_{\text{base}} = 1.0$. Times (non-dimensional) shown are 0.0, 4.88×10^2, 5.49×10^2, 6.63×10^2, 7.03×10^2, 7.18×10^2, respectively.

The ability to model complex tectonics, and address transitions in tectonic regime, minimally requires extremely temperature-dependent viscosity representations (Moresi and Solomatov, 1995), and the inclusion of some form of visco-plastic yielding (Moresi and Solomatov, 1998; Tackley, 2000), or an equivalent failure mechanism (e.g. Bercovici and Ricard, 2014). All the following models discussed have these prerequisites, though their assumed physical values vary significantly, reflecting the current state of unknowns. As an example, Bercovici and Ricard (2014) suggest a billion year lag between protosubduction, and continual tectonics, due to generation and accumulation of damage in their highly prescribed examples. A number of studies have demonstrated that these thermo-mechanical factors, largely impacting system stresses, exert a greater control on system behaviour than compositional effects (e.g. O'Neill et al., 2007a, 2007b, van Hunen and van den Berg, 2008; Sizova et al., 2010).

Both Stein et al. (2004) and O'Neill et al. (2007b) demonstrated that as mantle heat production increases, a simple "plate-tectonic" style mobile lid system will transit into an episodic regime, and eventually into a "hot" stagnant lid regime (Fig. 1). Though the higher temperatures affect internal velocities (convection is more rapid), the dominant effect is the dramatic drop in internal convective stresses associated with lower mantle viscosities. This was shown to be robust over a wide range of viscosity sensitivities (O'Neill et al., 2007b). The implications of a purely "tectonically-driven" episodic regime were discussed in O'Neill et al. (2007b, 2013b), Condie et al. (2009) and Condie and O'Neill (2010) and suggested to be appropriate to the Precambrian tectonic record. One implication of the regime diagram presented by O'Neill et al. (2007b) was that at even higher heat-production values than the

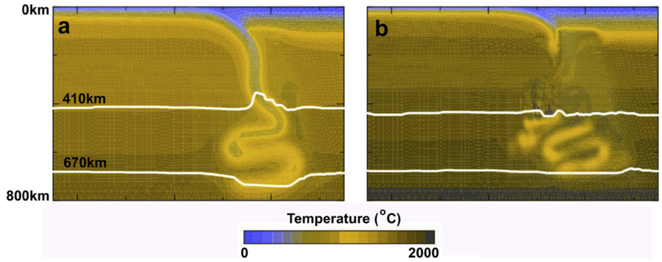

Fig. 2. (Adapted from Moyen and van Hunen, 2012.) Dynamics of subducting slabs for present day (a) or Archaean (b, $T = 200$ K hotter than present temperatures). The present day crustal thickness is 7 km, for the Archaean example it is 15 km, and snapshots are for after 15 Myr of subduction (left) or 4.5 Myr of convergence (right). Hotter mantle temperatures give rise to weaker slabs, which then "neck" and detachment into the mantle, resulting in intermittent subduction events.

Archean, appropriate for Hadean conditions, the tectonic regime may be stagnant.

van Hunen and van den Berg (2008) examined a simple subduction-zone configuration, with a weak (generally free-slip) fault, and an imposed weak mantle wedge region. Subduction was driven by the negative buoyancy of the slab, and they included the effects of compositional layering (more melting on the early Earth leads to a thick crust and harzburgite layer, hindering subduction), and eclogitisation (which facilitates subduction, as the transition from buoyant mafic crust to eclogite at depths $>\sim 40$ km results in a large density increase). The primary result of this work is that under hotter mantle conditions, weak slabs cannot transmit stress effectively, and tend to 'neck' and break off (Moyen and van Hunen, 2012). As a result, subduction under hotter mantle conditions cannot be continuous, but exhibits significant time dependence, as demonstrated by O'Neill et al. (2007b) for the Archaean. For the hottest temperatures explored ($\sim$300 K greater than present mantle potential temperatures), the models (after an initial pulse) did not exhibit subduction, and can be considered in a stagnant-lid mode. Moyen and van Hunen (2012) expanded these models to explore the short-term episodicity of Archaean tectonic cycles, suggesting the rapid switching between "arc-like" and "non-arc" volcanism (e.g. in the Western Abitibi, Ayer et al., 2004, and the Pilbara, e.g. van Kranendonk et al., 2007) may be related to very short lived (5–10 Myr) subduction events. They suggested this short subduction cycling was related to slab break-off/necking under hotter mantle conditions, resulting in an inherent episodicity to subduction. (See Fig. 2.)

The style of subduction seen in the aforementioned models is generally rather steep – at odds with previous suggestions that Archaean subduction may have been flat (e.g. Abbott et al., 1994; Martin, 1999). Flat subduction today occurs often due to the subduction of buoyant features such as oceanic plateaus or ridges (Gutscher et al., 2000; van Hunen et al., 2004). The argument postulates that due to high degrees of MOR melting in the Archaean, thickened oceanic crust should have been the rule, rather than the exception, which gives a compositional buoyancy to the oceanic lithosphere making it more difficult to subduct. An implication of this, argued by Davies (1992), would be that at some point, thickened oceanic crust would impart a sufficient compositional buoyancy to exceed the average negative thermal buoyancy of the plates, and subduction would cease.

This hypothesis was explored by van Thienen et al. (2004), who incorporated not only mantle melting and crustal formation, but also a basalt–eclogite phase transition (see Fig. 3). Basaltic crust thicker than $\sim$40 km may undergo a transition to eclogite, and, as eclogite is about 200 kg/m^3 more dense than mantle material, thus dramatically increasing the density of the subducting lithospheric package. van Thienen et al. (2004) found that this mechanism not only facilitated crustal recycling in the Archaean, but also

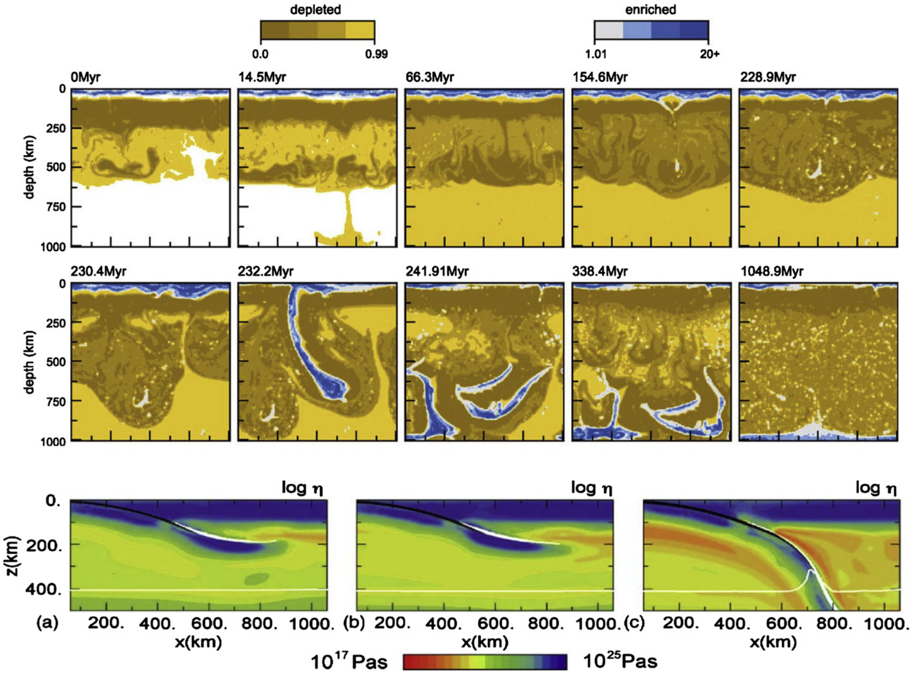

Fig. 3. Top: Snapshots of the compositional field for a convection simulation incorporating mantle depletion (dark yellow), and mafic crustal generation (blue), from van Thienen et al. (2004), used with permission. Undifferentiated mantle is shown as white. Mantle potential temperature is 1976 °C, crust is initially 30 km thick, and depth of modelling domain is 1005 km (see van Thienen et al., 2004 for further details). The thick buoyant crust is able to subduct due its transition to eclogite when thickened, resulting in an episodic mode of subduction. Bottom: Viscosity plots of 45 Myr old subducting slabs with an over-riding plate (overthrust velocity of 5 cm/yr), from van Hunen et al. (2004, used with permission). Snapshots are 12.8 Myr after subduction initiation, and are for (left to right) mantle potential temperatures of 1300 °C, 1338 °C, and 1375 °C, respectively. Basaltic crust is shown as black, eclogite as white, and the 410 km phase change shown as a white line. While flat subduction can be induced for present day temperatures, the kinetics of the eclogite transition result in fast convergence velocities and steep subduction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

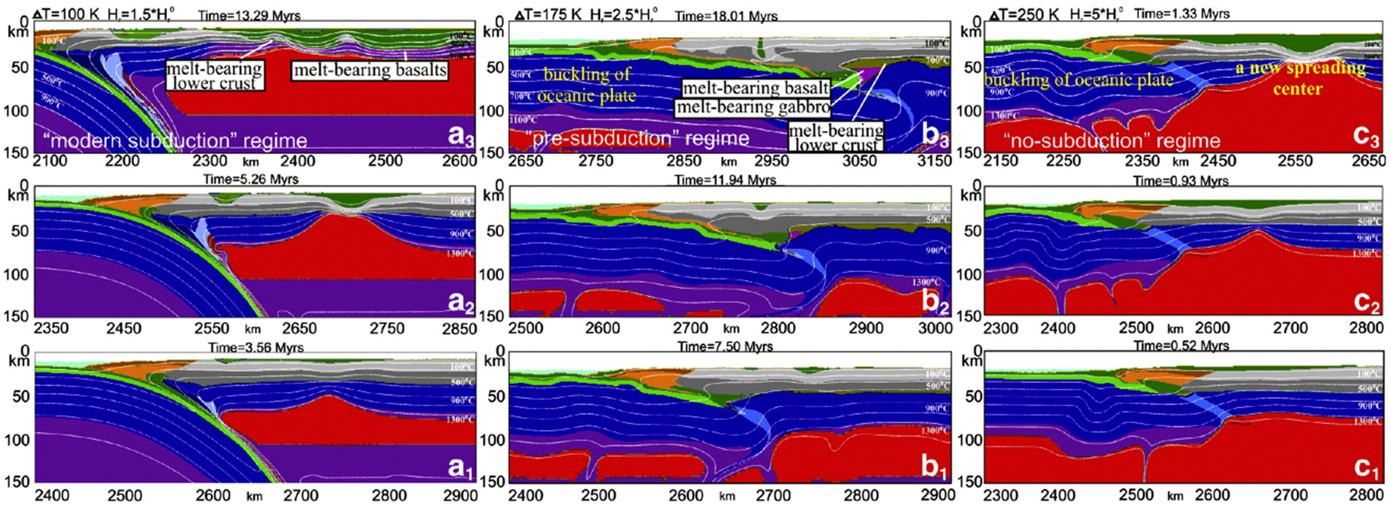

Fig. 4. Subduction style for increasing mantle temperatures, from the study of Sizova et al. (2010, used with permission). Simulations are for $\Delta T = 100$ K hotter than present day mantle, and $1.5 \times$ present day heat production (H), in a (left column, time series from bottom to top), b) $\Delta T = 175$, $H = 2.5 \times H_{\text{present}}$, and c) (right) $\Delta T = 250$ K, $H = 5 \times H_{\text{present}}$. Blue represents lithospheric mantle, purple asthenosphere, and red melt-bearing asthenosphere. For hotter mantle conditions, subduction ceases. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

imparted a strong episodicity in the dynamics of the subducting slabs.

van Hunen et al. (2004) explored the effect of the kinetics of the basalt → eclogite transition on subduction angle. This transition occurs at comparatively low temperatures (∼500–800 °C) at present-day flat subduction settings, and basalt may be metastable for up to ∼5 Myrs after passing the transition, giving rise to an intrinsic buoyancy of the slab, facilitating flat subduction. Under hotter mantle conditions, this reaction is faster, and the weaker, hotter mantle cannot sustain flat slabs under an advancing plate, and as a result the models of van Hunen et al. (2004) showed a prevalence of steep subduction for hotter mantle conditions – arguing that flat subduction is not feasible on the early Earth.

Sizova et al. (2010) explored the dynamics of an imposed subduction scenario under hotter mantle temperatures (see Fig. 4). Their models consisted of an oceanic lithosphere and crustal package juxtaposed against a continental margin, with an initial weak zone separating the two. The oceanic plates begin with a thermal age of 40 Myr, and are pushed towards the continents at a constant rate of 5 cm/yr. With this configuration, they demonstrated modern-style subduction at present-day mantle temperatures, including one-sided convergence, back-arc extension, and a hydrated, partially molten mantle wedge. For higher temperatures ($\Delta T > 175$ K present day temperatures), subduction evolved into a “transitional” (or “pre-subduction”) regime, characterised by extensive underthrusting of the oceanic plate, resulting in buckling and deformation of the continental lithosphere, and eventual two-sided subduction of the oceanic and continental lithospheric material. They note that the slab material may detach, and crustal material may be exhumed to higher levels in some examples. Though the prescribed dynamics of the system (a 5 cm/yr convergence velocity) preclude true episodic behaviour, the evolution of the slabs in the pre-subduction regime is very similar to that documented by van Hunen and van den Berg (2008) and O'Neill et al. (2007b). Further increasing the mantle temperatures ($\Delta T > 250$ °C above present day) results in the transition into a stagnant “no-subduction” regime, where horizontal motions are accommodated by internal strain within the lithosphere. Sizova et al. (2010) emphasise the importance of melt weakening on lithospheric strength. Increased lithospheric strength (in their models, due to less melt percolation, but also could also be due to cooler temperatures if initial plate thermal structure were varied) resulted in a tendency towards subduction, and weaker plates towards no-subduction.

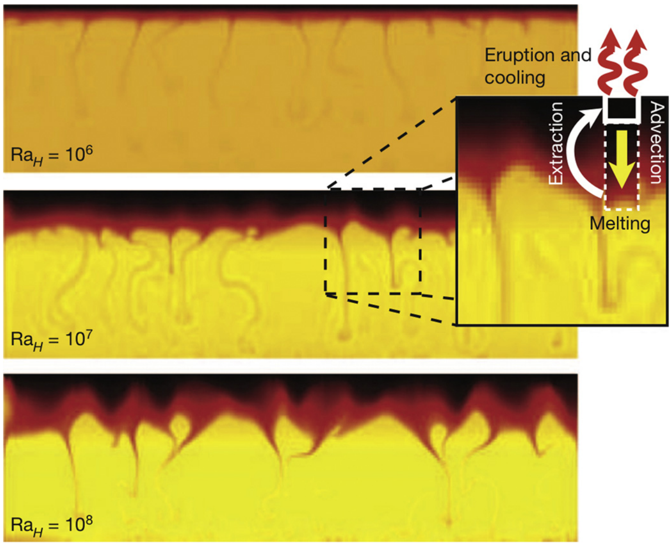

Fig. 5. Snapshots of the temperature field for convection with a parameterised heat-pipe model incorporated (from Moore and Webb, 2013, used with permission). Internal heating Rayleigh number varies from 10^6 (top) to 10^8 (bottom), and the inset demonstrates the heat pipe mechanism where melt is extracted to the surface, loading the lithosphere, which moves downwards, eventually and eventually melts again. Thicker lids for higher Rayleigh number are the result of efficient volcanic heat extraction by the heat pipe.

Moore and Webb (2013) explored the effect of volcanic heat pipes on early-Earth dynamics (see Fig. 5). They consider a vertical “conveyor-belt” involving the melting of peridotite, the transport of melt to the surface, and the loading of surface with solidified melt. Melt is primarily induced by downward-advecting lithosphere passing the peridotite solidus. They show that volcanic heat piping is an effective way of removing mantle heat, and argue for a natural transition from a heat-pipe model to modern subduction as heat production wanes. In many ways, the heat-pipe is effectively a (horizontally) stagnant lid. The maximum lithospheric stress in Moore and Webb's (2013) early heat-pipe regime is an order of magnitude lower than at present, and plate tectonics begins as internal temperatures drop and lithospheric stresses increase, similar to what is argued in O'Neill et al. (2007b). The model of

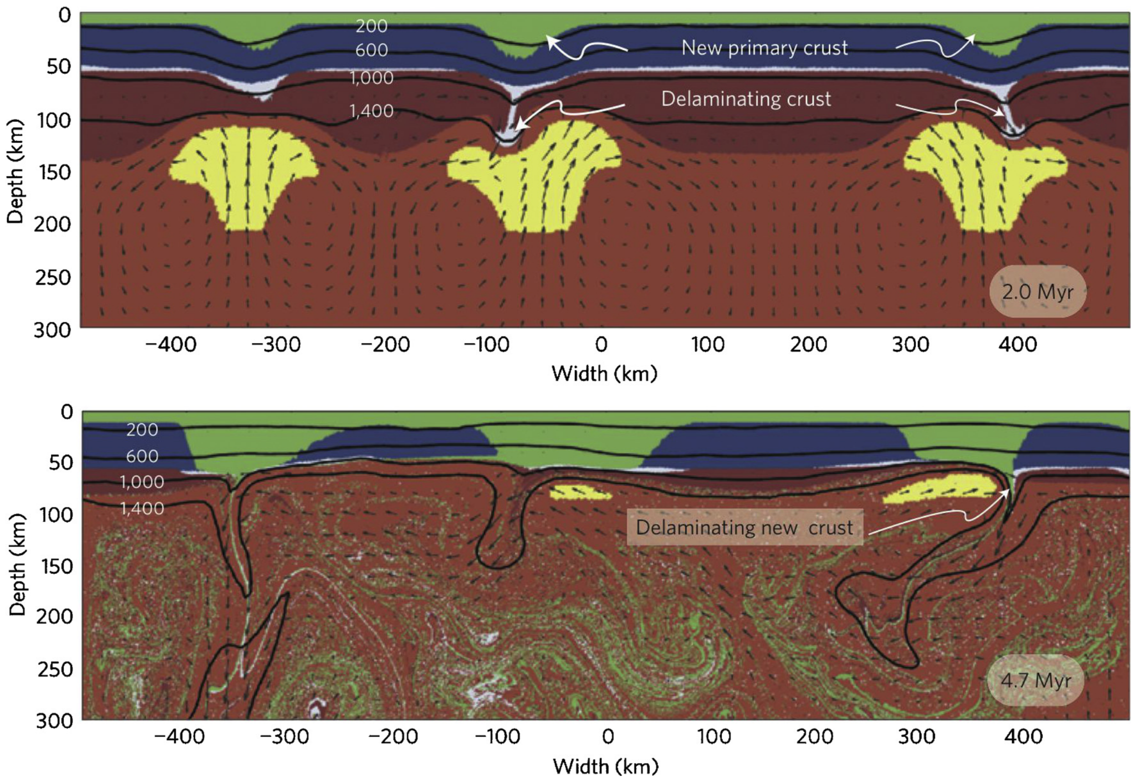

Fig. 6. Snapshots of a thermochemical simulation from Johnson et al. (2014, used with permission). Simulations begin with a 45 km thick crust (blue), which delaminates (light blue). Melt bearing asthenosphere (yellow) results in the addition of new primary crust (green), which may also be delaminated (bottom, at 4.7 Myr). Johnson et al. (2014) suggest this process, within a stagnant lid, could produce the hydrated Mg-poor basalts which melt to form TTGs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Moore and Webb (2013) does not include intra-lithospheric differentiation – they effectively consider the wholesale transport of an entire peridotite component to surface. In reality, the melting of peridotite would produce a mafic melt of different composition, leaving behind a more depleted residuum (e.g. O'Neill et al., 2005). This mafic melt, upon being added to the crust, may melt again due to burial or melt fluxing, to form more complex, differentiated melt. Denser, mafic (/eclogitic) residuums from the secondary differentiation may delaminate, resulting in a compositional evolution. It is not at all clear how melting proceeds in this model with a growing, depleted residuum. An additional issue is they do not consider emplacement of magmas within the crust/lithosphere, which would raise the calculated crustal temperatures considerably. The cases used as examples by Moore and Webb (2013), such as the early volcanic history of the Pilbara and Kaapvaal, are problematic in that they host rocks of low metamorphic grade (e.g. van Kranendonk et al., 2007), and are not really suggestive of wholesale downward motion of the crust/lithosphere. Nonetheless, the models demonstrate the importance of volcanic advection in stagnant-lid models, and are consistent with previous models arguing for the cessation of subduction on the early Earth.

Though the above models exhibit contrasting configurations, they all incorporate temperature-dependent viscosity, and yield stresses, and despite differing numerical schemes demonstrate similar physics. A few generalisations can be made from these results: 1) Under hotter mantle conditions, slabs are weaker and more likely to detach, resulting in time-dependent subduction. 2) Low mantle viscosities result in lower lithospheric stress levels, hindering yielding and subduction. This may induce a time dependence to subduction, or shut subduction down entirely. 3) Compositional effects are unlikely to shut-down subduction, due to eclogitisation of thickened crust, and the kinetics of eclogitisation suggest flat subduction is not really viable in the Archaean. Extrapolating the results of these simulations to the Hadean almost unilaterally suggests the Hadean/Eoarchaean was largely stagnant, with episodes of intermittent subduction. In the following section we address how this suggestion compares with the observational record.

3. How do the models compare with observations of the Hadean–Eoarchaean?

The Hadean has, until very recently, been characterised by the absence of a crustal record, which complicates comparisons with observations. The only purported example of Hadean crust (the Nuvvuagittuq greenstones in Quebec, O'Neil et al., 2012; Turner et al., 2014) has been implicated in the formation of later Eoarchaean suites (Adam et al., 2012). The relationship between these periods was transitional, and in all likelihood the delineation may be a preservational artefact – as a result we incorporate early Eoarchaean geology into our discussion of early Earth geodynamic constraints.

3.1. *TTGS and greenstones*

The Eoarchaean is dominated by tonalite–trondhjemite–granodiorite terranes (TTGs), and greenstone belts (Condie and Benn, 2006). The origin of TTGs is hotly debated, and they have been suggested to represent the melting of subducted oceanic crust under hotter mantle conditions (e.g. Martin and Moyen, 2002; Martin et al., 2005). The lack of a "mantle-wedge" signature in Archaean TTGs is purported to be due to flat-subduction (Martin and Moyen, 2002), however, the mechanism is inconsistent with numerical models as previously outlined (van Hunen et al., 2004). In contrast, Condie (2005) argues that trace element systematics suggest an origin in the partial melting of a hydrous lower crust. Bedard (2006) presents an intra-crustal differentiation sequence able to model the Douglas Harbour domain TTGs, within the Superior Province, by a remelting sequence of a thickened mafic crust.

Johnson et al. (2014) demonstrated the mineral assemblages at the base of a 45 km thick, hydrated or anhydrous, Mg-rich crust are more dense that the underlying residual mantle complement, if mantle temperatures are greater than ~1500–1550 °C (see Fig. 6). They present numerical models – in an effectively stagnant-lid regime – to demonstrate that the delamination and recycling of this crust is plausible under these mantle conditions, with the return asthenosphere flow generating more melt, and facilitating the ongoing enrichment of the crustal package. They note that this process could naturally produce the hydrated Mg-poor basalts which were the source for TTG melts. The gravitational instability of layered greenstone and TTG complexes may give rise to intra-crustal overturn (or "sagduction"), resulting in a dome-and-basin pattern, which is typical of many Archaean cratons (Thébaud and Rey, 2013; François et al., 2014).

Condie and Benn (2006) argue that up to 80% of Archaean greenstones older than 3.0 Ga display plume affinities (as opposed to arc-affinities), and that this ratio drops to ~35% by the late Archaean (3.0–2.5 Ga). Assuming these observations are not purely a preservational artefact, this is consistent with a predominantly stagnant surface in the Eoarchaean, with sporadic periods of surface mobility.

3.2. *Arc-plume record?*

A case is made by Moyen and van Hunen (2012) that interspersed "subduction" events in the western Abitibi (from 2.750 to 2.670 Ga), represented by volcanic and plutonic suites with "arc" affinities (i.e. a decoupling of large-ion lithophile elements from high field strength elements), occur as short-lived events (5–10 Myr). These short subduction events are superposed on a "plume" background, represented by plume-affinity volcanics. They argue a similar pattern is observed in the Paleoarchaean. In the eastern Pilbara terrane, and the Barberton Belt, short lived felsic volcanic events, suggested by Moyen and van Hunen (2012) to be subduction related, are interposed with thick mafic volcanic packages (e.g. van Kranendonk et al., 2007; Lowe and Byerly, 2007), putatively representing plume-related activity.

These repetitive interwoven plume-arc events (e.g. Wyman et al., 2002), and the short timescale of arc-volcanism (Moyen and van Hunen, 2012), are consistent with an "episodic" mode of convection, where a stagnant lid is intermittently interrupted by sporadic, short-lived subduction events.

3.3. *Subduction initiation sequence*

Turner et al. (2014) argued that the volcano-stratigraphic sequence of subduction initiation in the Izu–Bonin–Mariana (IBM) forearc has parallels with the volcano-stratigraphy of the Nuvvuagittuq greenstones in Quebec, which have model ages of 4.4–4.3 Ga (O'Neil et al., 2012) – though they might be as young as 3.8 Ga (Cates et al., 2013). The stratigraphy begins with forearc basalts related to the initial fracturing of the lithosphere, and decompression melting of the asthenosphere, characterised by flat HFSE-REE patterns. As subduction begins, released fluids initially flux through a refractory, depleted mantle (e.g. over-riding lithosphere), resulting in boninites with strongly depleted HFSE-REE, and associated with either BIFS (in the Nuvvuagittuq) or hydrothermal ore (in the IBM). As subduction matures and an asthenospheric mantle wedge develops, the volcanics evolve to typically calc-alkaline affinities (arc andesites in the IBM, low-Ti enriched mafic rocks in the Nuvvuagittuq).

If true, what is remarkable is that rather than a subduction zone signature, it is a subduction initiation event that is recorded – a reasonably rare event in the Phanerozoic, and profoundly so for the only known purportedly Hadean outcrop. This might suggest that rather than mature subduction zones, subduction initiation events were more common, which parallels the observations of Moyen and van Hunen (2012) or O'Neill et al. (2007b) on the episodicity and short-lived nature of Archaean subduction zones.

3.4. *Jack Hill zircons*

Early work on the Hadean-aged Jack Hills zircon population (Harrison et al., 2005) posited a predominantly felsic source for the zircons. Harrison et al. (2005) suggest on the basis of Lu/Hf that this early crust was extensive, and, by analogy to continent formation at present, suggest equivalent plate boundary processes must have operated in the Hadean. This view was reinforced by Watson and Harrison (2005) who documented wet, minimum melting granites at approximately ~700 °C – equivalent to those formed at plate margins today. Further work on the thermobarometry (Hopkins et al., 2008) suggested heat flows around ~75 $\mathrm{mW/m^2}$, which were suggested to be characteristic of convergent margins. While fore-arc environments typically show low heat flows, volcanic arcs and back-arcs today (the former being where most granites are formed) can have – comparatively – very high heat flows (Currie and Hyndman, 2006). Low comparative heat flows are, however, expected both in a stagnant lid, particularly between episodes of significant lid recycling (e.g. Condie and O'Neill, 2010), and also in the "heat-pipe" model of Moore and Webb (2013) for the Hadean. These atectonic regimes are capable of extensive crustal melting during plume and/or heat pipe volcanism (Johnson et al., 2014). Furthermore, were the Jack Hill zircons unequivocally convergent-margin related, it is equally likely that they represent the discrete subduction events typical of O'Neill et al. (2007a, 2007b) and Moyen and van Hunen (2012), rather than continuous plate tectonics.

The interpretation of the Jack Hills record is equivocal, however, as further work by Kemp et al. (2010) and Griffin et al. (2013), looking at the least altered grains, argued that the protolith which melted to form the majority of zircons may have been primarily mafic. Kemp et al. (2010) further suggest that there is no evidence for widespread depletion of the Hadean mantle (cf. Harrison et al., 2005), and that the mafic protolith may in fact have been the primordial crust, which formed during the crystallisation of the terrestrial magma ocean. Kemp et al. (2010) argue that there is no evidence for significant crustal addition to the Jack Hills protolith during the Hadean. They suggest the protolith's residence time – during which it produced the Jack Hill's zircon suite – was around 400 Myr (see Fig. 7). This is an extraordinary long time for a thick mafic package to remain at surface, particularly in the Hadean (compared to, for instance, oceanic crust lifetimes today). O'Neill et al. (2013a) argued that this long residence time is what is expected if the Hadean was primarily stagnant, with only short intermittent subduction events.

The Hadean zircon record is equivocal regarding both composition of the Hadean crust, and tectonic implications. Though it has been argued that Hadean zircons support early plate tectonics, an equally valid argument suggests a long-lived stagnant crust, and additional constraints are needed to bear on the debate.

3.5. *Mantle mixing*

A number of lines of evidence suggest mantle mixing in the Hadean was quite slow (>1 Gyr). ^{142}Nd anomalies are formed due to early Hadean crustal fractionation events, and the signatures of these events may be preserved in younger rocks (e.g. Caro et al., 2003, 2006; Bennett et al., 2007; Murphy et al., 2010; Cipriani et al., 2011). Debaille et al. (2013) found ^{142}Nd anomalies in a 2.7 Ga

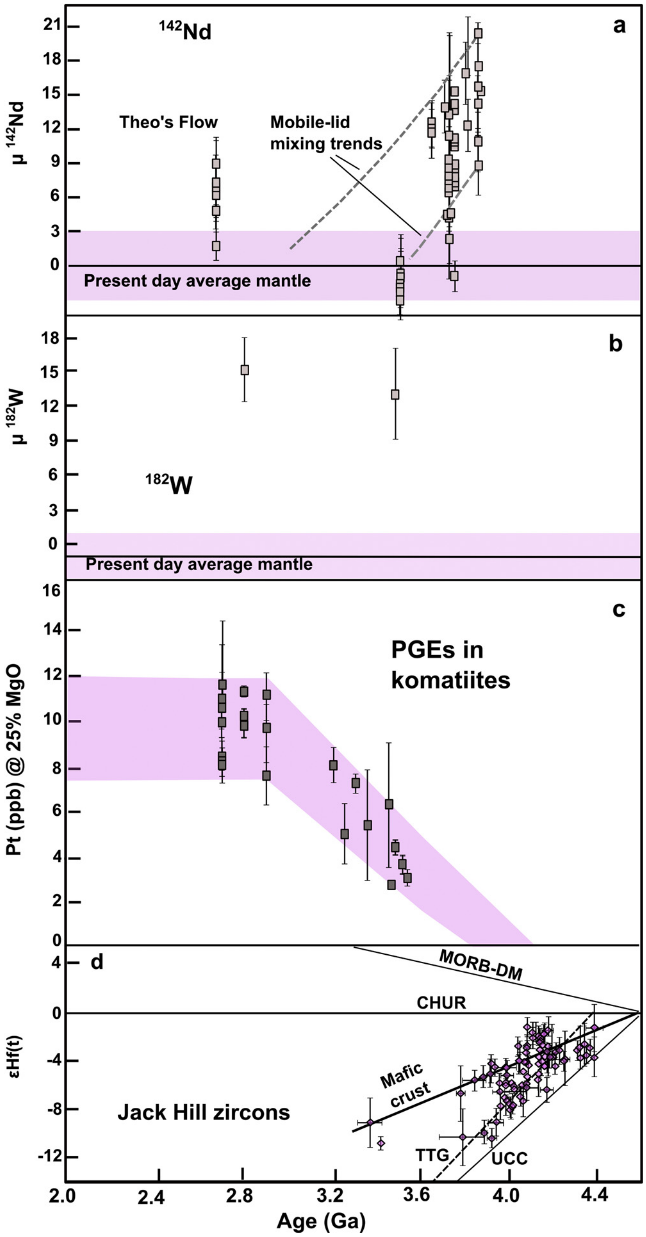

Fig. 7. a) μ^{142}Nd model ages, from dataset compiled in Debaille et al. (2013), suggesting >1.5 Gyr mixing times for these heterogeneities. b) ^{182}W anomalies from Willbold et al. (2011) and Touboul et al. (2012), also suggesting long mixing times for these isotopic heterogeneities. (c) Concentration of Pt (as a proxy for platinum group elements) in komatiites through time, showing this late veneer contribution was not mixed in entirely till ~2.9 Ga – a mixing time of over 1.5 Gyr. d) εHf(t) vs age for unaltered Jack Hills zircons (modified from Kemp et al., 2010). The least altered were produced from a mafic protolith, which survived, and was sampled, for over 400 Myr.

tholeiitic lava flow from the Abitibi Greenstone Belt, indicating that early mantle heterogeneities survived for ~1.8 Gyr (Fig. 7) – far beyond the ~90 Myr timescales expected from convection theory (e.g. Coltice and Schmalzl, 2006).

Other systems show similar mixing times. ^{182}W anomalies represent primordial partitioning events in the Hf–W system. Willbold et al. (2011) found ^{182}W anomalies in the 3.8 Ga samples of $\sim\mu^{182}\text{W} = +13 \pm 4$. More recently, Touboul et al. (2012) found ^{182}W anomalies in 2.8 Ga komatiites from the Kostomuksha Greenstone Belt – suggesting mixing times of ~1.7 Gyr. The Gadwal greenstone belt (Dhawar craton, India) records the preservation of Lu/Hf and Sm/Nd ratios over ~1.8 Gyr (Khanna et al., 2014).

Similarly, platinum-group elements (PGEs) in the mantle are thought to be largely due to a "late-veneer" of meteoritic material, which postdated core-formation, and which seems to have been fairly short lived (e.g. Day et al., 2012). Maier et al. (2009) explored the evolution of PGEs in komatiites through time, and found they did not reach their present concentrations in the mantle until 2.9 Ga. PGEs in the komatiitic source appear to systematically increase from 4.0 to 2.9 Ga, presumably as the late veneer material was progressively mixed into the mantle, independently suggesting mixing times of >1.6 Gyr.

These isotopic/element systems have very different origins, and their survival is not easily explained by resorting to high-viscosity mantle domains (e.g. the lower mantle, or mantle blobs). In particular, ^{142}Nd represents an upper mantle anomaly, and PGEs were probably deposited in the near-surface, so the delay in their mixing probably reflects the timescale of mixing between the surface and convecting mantle interior.

Debaille et al. (2013), and O'Neill et al. (2013a) explored the effect of tectonics on mixing, and found that mixing in a stagnant-lid regime (in 2 or 3D) is an order of magnitude less efficient than plate-tectonic mixing. Both studies suggest that the discrepancy in Hadean mixing times can be resolved if the early Earth was primarily stagnant, with perhaps a number of short-lived subduction events.

3.6. *Thermal evolution models*

Simple energy-balance models for Earth's evolution traditionally assume that Earth's heat loss is a function of internal heat generation (treated as a known throughout Earth's history), and secular cooling. This heat loss, cast as the Nusselt number (the non-dimensional ratio of convective to conductive heat flux), can also be related to Rayleigh number, a measure of convective cooling. The Rayleigh number depends on the system temperature contrast – which ties it to secular cooling, creating a coupled system of equations, which can be solved to give Earth's thermal history – but only if the relationship between Nusselt number and Rayleigh number is known.

Traditionally, a $\text{Nu} \sim \text{Ra}^{1/3}$ scaling has been applied to such models, as this exponent fits well with laboratory models for (primarily isoviscous) convection, and also numerical models for mobile lid convection (e.g. Moresi and Solomatov, 1998). It should be emphasised, that in both cases lid-overturn is implicitly assumed in the choice of exponent.

This leads to a problem in Earth thermal history models (see Fig. 8). Since the heat loss due to plate tectonics is so high, for sensible values of heat generation, the internal temperatures must have been much higher in the past to balance this flux. This quickly leads to a pathological behaviour known as the Archaean thermal catastrophe, where for given internal heating rates, and assuming a plate tectonic scaling, temperatures are estimated to be greater than 1800 °C at 1500 Ma – implying the whole mantle was molten. This is clearly at odds with observational constraints on mantle temperatures (e.g. Herzberg et al., 2010), and suggests an internal inconsistency in the model. Traditional explanations invoking hidden (or poorly constrained) heat sources are unviable, or simply push the problem back in time (e.g. O'Neill et al., 2013a). Other factors including the evolution of continents (Lenardic et al., 2011) also push the problem further back in time, but do not eliminate it. Korenaga (2006) suggested elastic plate effects may alter the evolutionary trend, but this has been criticised by Davies (2009) who suggested this factor is unlikely to be significant throughout Earth's history due to reconfigurations in curvature – consistent with the second order effect of elasticity found in plate models including Maxwell viscoelasticity (e.g. O'Neill et al., 2007a).

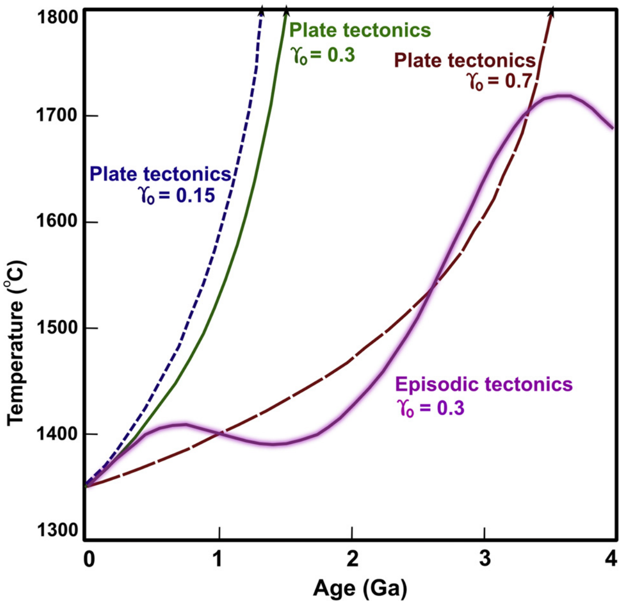

Fig. 8. Parameterised thermal evolution models of the Earth, modified from O'Neill et al. (2013a), Korenaga (2006), and Silver and Behn (2008). A simple plate tectonic scaling (assuming a mobile lid) with Urey ratios (γ_0) of 0.15, 0.3 or 0.7 result in unacceptably high temperatures when integrated into the past. The episodic tectonic curve of Silver and Behn (2008), with a Urey ratio of 0.3, does not result in a thermal catastrophe, due to limited cooling rates during stagnant episodes.

Silver and Behn (2008) demonstrated that if one relaxes the Nu $\sim$ Ra$^{1/3}$ assumption – i.e. relaxes the assumption of lid mobility, the problem may be alleviated. In their intermittent plate tectonic model, the decreased efficacy of heat loss during periods of non-subduction, means that less extreme temperatures are required in the past. Counter-intuitively, early Earth's main problem was not getting rid of heat fast enough, but getting rid of it slow enough to explain present-day mantle temperatures and heat flux – a problem that it alleviated if the early Earth was stagnant, or episodically overturning, during its earliest history.

3.7. Paleointensity measurements

The strength of the magnetic field is strongly dependent on heat flux across the core–mantle boundary (e.g. Buffett, 2000), among other factors. High CMB heat flux is commonly associated with cold slabs arriving at the CMB. Without subduction, the core sees an internally hot mantle as its upper boundary, resulting in lower CMB heat flows, and a less effective geodynamo. Previous modelling has suggested a correlation between plate tectonics, and a core dynamo on early Mars, which conceivably shut off due to the cessation of tectonic activity (Nimmo and Stevenson, 2000; Elkins-Tanton et al., 2005).

Paleointensity measurements by Macouin et al. (2004, 2006) documented large variations in the Precambrian paleomagnetic field. O'Neill et al. (2013b) suggested the peaks in paleointensity in the Precambrian follow rapid subduction events, which are reflected in apparent-polar wander paths and the geological record (e.g. Condie et al., 2009). Cottrell et al. (2012) extend these paleomagnetic measurements back to 3.47 Ga, examining single silica crystals in granites from the Duffer formation in the Pilbara. They find the magnetic field strength at this time was $\sim$25% of its present value. More recently, Tarduno and Cottrell (2013) presented the results of a conglomerate test of the Jack Hills metaconglomerate, suggesting the survival of a high-temperature remanance. They note both Ti-in-quartz and monzonite thermobarometry both give maximum temperatures for the formation in the range of 346–487 °C, below the Curie temperature of many magnetic inclusions (e.g. magnetite). Tarduno and Cottrell (2013) and Cottrell et al. (2013) presented new data on zircons from the Jack Hills formation. Though they have only measured one demonstrably Hadean zircon ($\sim$4.1 Ga), they showed a similarly low magnetic field strength during this interval. Not only are paleointensity measurements difficult, but dynamo strength variations may conceivably be due to a number of factors. However, CMB heat flow exerts a first order effect, and taken at face value, in the context of the previous discussion, these low field strengths are at least consistent with stagnant lid convection throughout much of the Hadean.

4. Conclusions and directions

In a paper on possibly the earliest recorded subduction event, Turner et al. (2014) argue that numerical models have been equivocal as whether plate tectonics may have operated in the Hadean. In contrast, here we have summarised a diverse suite of models from different groups, utilising different numerical schemes, which possess the ingredients to model plate-like behaviour – namely temperature-dependent viscosity, and a yield criterion. On increasing mantle heat generation to Hadean levels, subduction in these models unequivocally shuts down.

Whilst these different groups have at times focused on different parts of the same problem (lithospheric stresses, vs. slab strength, or melt-induced weakening of the lithosphere), and utilised very different configurations and boundary conditions, the net result is that the balance of induced stresses from the mantle (or boundary velocity) cannot generate sufficient stress in the over-lying plates to sustain subduction. The solidarity between these very different models is not well recognised outside the Precambrian convection community (e.g. Gerya, 2014).

What's more, a stagnant, or episodic subduction, evolution for the Hadean is consistent with much of the available constraints for the Hadean/Eoarchaean. From the basic geological observations supporting Eoarchaean episodic subduction, to the stagnant protolith to the Jack Hills zircons, to mantle mixing constraints and thermal history models – a stagnant to episodic evolutionary model provides a coherent context and framework for these observations. A plate-tectonic framework runs into difficulties with a number of these constraints, as previously discussed.

So, it is argued here there exists a coherency between existing model results, and available observations, for the early stagnant/episodic evolution of the Hadean/Eoarchaean. It is pertinent to consider what more is needed to bolster the case; as it turns out, this comes to rather a lot.

The modelling for this epoch is far from mature. Recent work has outlined the critical nature of initial conditions on evolutionary convection models (Crowley and O'Connell, 2012; Weller and Lenardic, 2012), and the application of this result to the Earth is crucial. But what is an appropriate condition for the post-magma ocean Earth? What is the thermal state, and scale of heterogeneities? Was there post magma-ocean chemical layering? What of the importance of large impacts during the Hadean? Or atmospheric evolution? We are only beginning to address these problems.

Prior to 2001, the Hadean had been considered a geological dark age, due to the absolute paucity of data from this epoch (e.g. Halliday, 2001). This is hardly the case today. Not only is there vigorous debate over the possibly Hadean Nuvvuagittuq locale (O'Neil et al., 2012), but a wealth of information exists from Hadean zircons (e.g. Kemp et al., 2010). Isotopic measurements on younger rocks are constraining Hadean processes (Debaille et al., 2013), and new techniques, such as paleointensity analysis, are bearing fruit (Cottrell et al., 2013).

As is often the case in science, some of the most critical advances in Hadean geodynamics are at the intersection of the observational and theoretical fronts. Though both face significant technical challenges, the reward is an understanding of how Earth came to be, which might be seen to be worth it.

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